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Flavor Quality in *Rosaceae* Fruit and Nut Crops: "Insights into Volatile Organic Compounds and Recent Breeding Strategies"

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Abstract

The rose family (*rosaceae*) is of great importance because it includes a variety of edible fruits such as apples, pears, peaches, plums, cherries, almonds, strawberries, loquat, and raspberries but its flavor quality wasn't the best. The positive impact of flavor quality on consumers and, most importantly, breeding industries can never be overemphasized. Even in the developed world, fruits with quality flavor undoubtedly impact overall health by shifting eating habits away from ceremonial food to daily meals. Although fruit flavor has considerable benefits to consumers, it is difficult to improve, requiring the integration of several complex biochemical pathways controlled by developmental, physiological, and environmental factors. Hence, this paper reviewed the flavor compounds composition of *rosaceous* fruits and nuts including the factors influencing their contents and concentrations, commonly found volatile organic compounds in *rosaceous* fruits and nuts, and breeding strategies and challenges in breeding for flavor in *rosaceae* fruits and nuts. Breeding strategies for improving fruit flavor include molecular-assisted breeding (MAB) and transgenic approaches.Both strategies will developfruit varieties that not only meet market demands but also provide superior taste and nutritional benefits for consumers.

Keywords: Breeding strategies, Flavor, *Rosaceae*, Volatile Organic Compounds

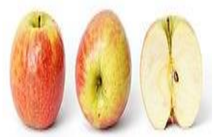
Introduction

In recent times, consumer preferences for fruits and nuts have shifted towards those with appealing flavors, prompting growers, scientists, and nutritionists to prioritize flavor traits. While initial purchases may be influenced by factors like color and firmness, repeat purchases heavily hinge on taste and aroma. Historically, breeders concentrated on quantifiable traits like size and yield, often overlooking flavor's impact on marketability and consumption rates. However, heightened health awareness has spurred demand for high-flavor fruits, necessitating a reevaluation of breeding priorities (Aubert et al., 2010).

Flavor is a complex amalgamation of sweetness, sourness, bitterness, acidity, saltiness, and aroma, primarily composed of volatile organic compounds (VOCs). VOCs, which evaporate at room temperature, are influenced by various factors including harvest maturity, environment, and genetics (Dimick et al., 1983, Baldwin et al., 2007). The aroma of fresh produce influences perceptions of sweetness and sourness, enhancing overall palatability. In the case of *Rosaceae* fruits and nuts, VOCs contribute significantly to their unique aroma profiles (Ayala-Zavala et al., 2004; Bureau et al., 2006). These compounds are synthesized during fruit development and maturity, with variations in availability and concentration among different fruit tissues. *Rosaceae* fruits, including apples, pears, plums, cherries, and strawberries, are widely consumed globally, with consumer judgments often based on sensory perceptions of flavor (Baldwin et al., 2007)

The composition of VOCs varies among *rosaceae* fruits, with certain compounds playing pivotalroles in aroma character. For example, apples contain over 300 VOCs, with ester compounds dominating loquat (Yahia, 1994; Pino et al., 2002; López et al., 2007; Malowicki, 2007; Sun et al., 2010; Agila and Barringer, 2012). Similarly, strawberries boast a rich VOC profile, dominated by esters like ethyl butanoate and methyl butanoate (Buttery, 1981). Factors such as maturity, storage conditions, and chemical treatments influence VOC development (Tressl et al., 1985; Matthais et al., 1992; Fellman et al., 2003).Breeding strategies such as molecular-assisted breeding and transgenic approaches offer promising avenues for flavor enhancement, despite the challenges they face. As the demand for flavorful and nutritious fruits continues to grow, the integration of flavor improvement strategies into breeding programs will be essential for meeting consumer preferences and improving public health. The future of fruit breeding lies in the ability to combine traditional methods with modern genetic techniques to create superior fruit varieties that satisfy both market demands and nutritional needs. Thus, this paper advocates for a comprehensive understanding of flavor compound composition and factors influencing VOCs, alongside breeding strategies for flavor enhancement to ensure consumer satisfaction.

Table 1.**Taxonomy and Representation of Rosaceae Family**

Kingdom	Family	Genus	Species	Common name	PICTURE
Plantae	Rosaceae	Malus	M. domestica	Apple	
Plantae	Rosaceae	Fragaria	F. × ananassa	Strawberry	
Plantae	Rosaceae	Rubus	R. idaeus	Raspberry	
Plantae	Rosaceae	Prunus	Prunus cerasus	Cherry	
Plantae	Rosaceae	Prunus	Prunus domestica	Plum	
Plantae	Rosaceae	Prunus	P. amygdalus	Almond	

Plantae	Rosaceae	Prunus	P. persica	Peaches/Nectarine	
Plantae	Rosaceae	Pyrus	Pyrus communis	Pear	
Plantae	Rosaceae	Eriobotrya	E. japonica	Loquart	
Plantae	Rosaceae	Prunus	Armeniaca	Apricot	
Plantae	Rosaceae	Cydonia Mill.	C. oblonga	Quince	

Aroma Perception and Sensory Experience

Volatile organic compounds (VOCs) in fruits and nuts serve multifaceted roles, including defense against stresses, facilitation of plant interactions, and enhancement of reproductive success (Laothawornkitkul et al., 2008; Schwab et al., 2008). They function as antimicrobial and antifungal agents, safeguarding plants from pathogens. Compounds like methyl jasmonate and limonene exhibit allelopathic effects, inhibiting the growth of competing plants and pathogens. Limonene, specifically, regulates plant attractiveness and resistance to pathogens. Isoprene aids in plant-herbivore interactions by deterring feeding and protecting photosynthesis from high temperatures. S-linalool repels pathogens due to its antimicrobial properties, while sesquiterpenes attract nematodes that target insect larvae hosting pathogens (Rasmann et al., 2005; Dudareva et al., 2007; Laothawornkitkul et al., 2008; Loivamaki et al., 2008; Schwab et al., 2008). Moreover, VOCs play a crucial role in plant reproduction by attracting pollinators and seed disperser (Schwab et al., 2008). Isoprene emissions have been linked to early flowering in various plant species, suggesting a role in pollination. Additionally, VOCs help distinguish between ripe and unripe fruits, aiding in seed dispersal and fruit selection by animals. Economically, VOCs significantly impact food quality and flavor, contributing to the palatability and appreciation of foods. They are highly valued in the food industry, with an estimated annual global consumption exceeding 5000 tonnes and a market value of over US $18 billion (FAOSTAT, 2008).

Overall, VOCs in fruits and nuts play pivotal roles in plant physiology, ecological interactions, and food quality, contributing significantly to both natural ecosystems and human society.

Category of Volatile Organic Compounds in Rosaceae

Rosaceae fruits and nuts have diverse volatile organic compounds (VOCs), classified into esters, alcohols, aldehydes, ketones, lactones, terpenes/terpenoids, and miscellaneous (hydrocarbons) as shown below in figure 1. However, not all contribute to the overall flavor. For example, in apples, only 30-50 out of hundreds of VOCs impact aroma (Dixon and Hewett, 2000; Mehinagic et al., 2006; Shimizu et al., 2024). Raspberry's aroma is mainly attributed to raspberry ketone (Lee, 2016; Lim and Choi, 2021; Rao et al., 2021).

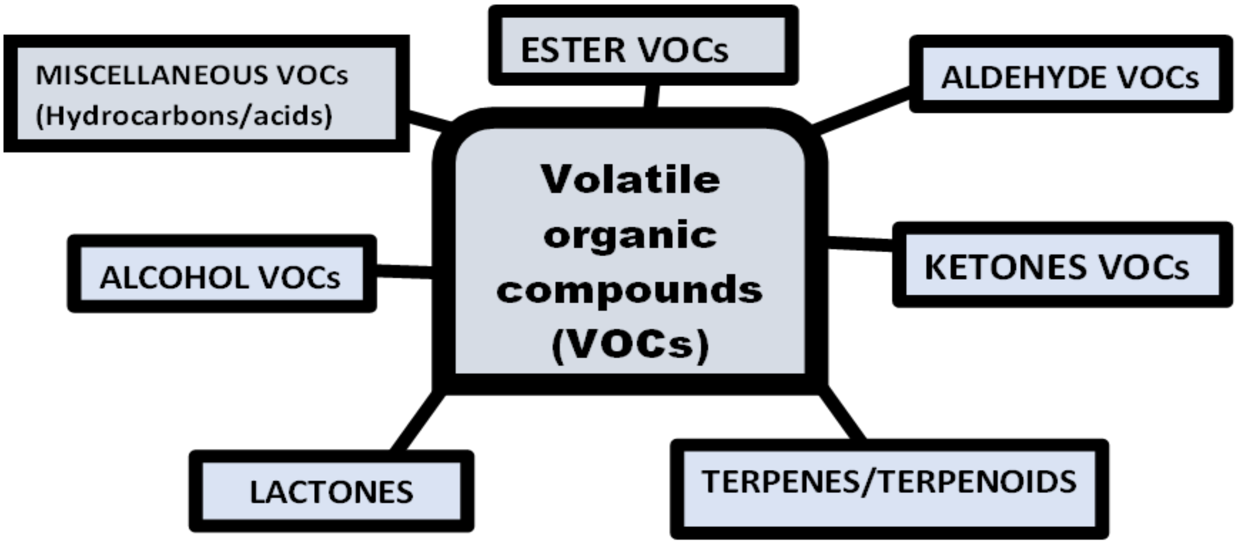


Figure 1: categories of Volatile Organic Compounds in *Rosaceae* Fruit and Nuts.

Compositions of Volatiles in the Fruits and Nuts of Different Species of Rosaceae plants

Apple (Malus x Domestica Borkh): The flavor of apple fruit is a complex interplay of various chemical compounds, including esters, aldehydes, alcohols, terpenes, ketones, lactones, and hydrocarbons. Esters stand out as the most abundant volatile organic compounds (VOCs) in apples, constituting over 30% of the total (Berger, 2007; López et al., 2007; Guerra, 2009). Compared to other rosaceous fruits, apples exhibit higher ester content. Common ester VOCs in apples includes ethyl acetate, ethyl butanoate, and ethyl hexanoate. Alcohols, the second most abundant aroma compounds, contribute fruity flavors, while aldehydes impart green, fruity, grassy, and earthy notes (Yahia, 1994; Ferreira et al., 2009). Lactones, though less common, contribute to fruity and nutty flavors. Apples also contain higher levels of ketones compared to certain fruits like pears and cherries, lending floral, woody, bitter, and nutty aromas. Additionally, acids and hydrocarbons are present, outnumbering other VOC classes. Terpenes like alpha-farnesene and beta-farnesene further enrich the aroma profile of apples (Berger, 2007; López et al., 2007). Understanding the composition and concentrations of these VOCs is crucial for characterizing apple flavor and enhancing consumer satisfaction.

Strawberry (Fragaria X ananassa): Strawberries exhibit a rich array of volatile organic compounds (VOCs), with esters comprising over 20% of all VOCs, notably higher than in other *rosaceae* plants (Buttery, 1981; Pyssalo et al., 1979; Forney et al., 2000). Common esters like ethyl butanoate and methyl butanoate contribute significantly to aroma impact (Buttery, 1981; Forney et al., 2000; Beekwilder et al., 2004). Alcohols, accounting for over 5%, play a minor role in the aroma profile (Jetti et al. 2007; Kafkas et al., 2012). Aldehydes, responsible for green and floral notes, contribute over 10%, with hexanal and trans-2-hexenal being prominent (Jetti et al. 2007; Kafkas et al., 2012). Lactone concentrations vary by cultivar, with some showing higher levels than others. Ketones constitute a small proportion compared to other *rosaceae*, possibly explaining their minimal impact on aroma. Terpenes, comprising less than 10%, contribute pleasant citrus and spicy notes). Strawberry contains miscellaneous compounds which include organic acids acid and hydrocarbons. These miscellaneous are less in number than those in apple, loquat, and almond (Zorrilla-Fontanesi et al., 2012).

*Raspberry (Rubus ideausL.):*Like other *rosaceae***,** contains ester compounds though in fewer amounts when compared to other berry families such as strawberry, high-bush blueberry, and low-bush blueberry and some *rosaceae* families including apple, plum, apricot, peaches, and nectarines (Klesk et al., 2004). Volatile esters play a contributory role in the overall raspberry flavor and not as an aroma impact compound (Farneti et al., 2023). Alcohol compounds account for a wide range of 20% of volatile organic compounds in raspberry (Forney, 2001). The volatile alcohols have a major contribution to raspberry aroma (Klesk et al., 2004). Alcohol volatiles are responsible for floral, pungent, hot tea, lemon-sweet, perfumery, and watermelon, in raspberry (Table 1). Aldehydes play an influential role in raspberry character impact flavors even though it’s less abundant in raspberry. The most abundant aldehyde compound in raspberry is benzaldehyde (Forney, 2001; Aprea et al., 2015). Lactones in raspberries are less ample than ketones, aldehydes, esters, alcohols, and terpenes (Table 1) (Honkanen et al., 1980; Forney, 2001; Kafkas et al., 2019). The most common lactone in raspberry is shown in table 1**.** Ketones are one of the aroma character impact compounds in raspberry (Table 1). Studies suggest that 4-(4-hydroxyphenyl)-butan-2-one is a major character impact aroma compound (Larsen et al., 1990; Roberts and Acree, 1996; Estrada-Beltran et al., 2020). Ketone volatiles in raspberry are responsible for the sharp, green, pungent, mushroom, and woody flavor notes in raspberry. Raspberry contains a relatively high number of terpenes. The terpenes alone constitute over 20% of VOCs in raspberry (Latrasse, 1991; Forney, 2001; Giongo et al., 2019). The relative amounts of terpenes isolated from the headspace of three-raspberry cultivars reported by Shamaila et al. (1993) showed that α-pinene, β-myrcene, and γ-terpinene are higher in concentration than other terpenes. Raspberry fruits contain many hydrocarbons and organic acids which underwrite their aroma impact flavor (Latrasse, 1991; Forney, 2001; Sangiorgio et al., 2022).

*Sweet Cherry (Prunus avium L.):*Sweet cherry possesses a wide range of volatile organic compounds (VOCs) common in other *rosaceae* fruits, albeit in lesser quantities for some compounds like esters, lactones, terpenoids, and ketones compared to almonds and other *rosaceous* fruits (Mathias *et al*., 1991; Mathias *et al*., 1992; Girard and Kopp, 1998; Nikićević*et al.,* 2011). Although sweet cherries contain fewer esters, those identified contribute to fruity aromas, notably in Bing cultivars (Sun *et al*., 2010; Legua*et al.,* 2017). While volatile alcohols are not major aroma impact compounds, they play contributory roles in imparting fruity and floral notes. Aldehydes, notably benzaldehyde and phenylacetaldehyde, are abundant and significantly impact cherry flavor (Mathias et al., 1991; Mathias et al., 1992; Sun et al., 2010). Ketones are not prevalent in sweet cherries. Terpenes and lactones are absent, but miscellaneous compounds like hydrocarbons and organic acids contribute to the overall aroma profile (Serradilla et al., 2010).

Pear-European pear (*Pyrus communis L.*) *and Asian pear* (*P. pyrifolia Nakai*): Pear possesses moderate to high levels of volatile organic compounds (VOCs), with esters being the most abundant (Rapparini and Predieri, 2003). Alcohol compounds are minimal, representing less than 10% of all VOCs, while aldehydes are common, contributing to pear's aroma profile. Unlike other *Rosaceae* fruits, pears contain no lactones, with fewer terpenes/terpenoids and ketones. Farnesene in pears contributes to a green, apple-like aroma (Takeoka et al., 1992; Suwanagul and Richardson, 1996; Li et al., 2012).

Peach and Nectarine (*Prunus persica L.*): Peach and nectarine are rich sources of aroma compounds, with esters being prominent contributors to their fruity aroma (Aubert and Milhet, 2007; Wang et al., 2009; Seker et al., 2011; Sánchez et al., 2012). Alcohol content is minimal, slightly higher in peach than nectarine (Wang et al., 2009; Seker et al., 2011; Bavcon-Kralj et al., 2014). Aldehydes are relatively higher and contribute to almond, citrus, and floral notes. According to Bononi et al. (2012) lactones, responsible for sweet flavors, are more abundant in peaches and nectarines compared to other *rosaceae* fruits. Ketones in peaches impart polish-like aromas, while terpenes/terpenoids are relatively high (Wang et al., 2009; Eduardo et al., 2010; Montero-Prado et al., 2013). Hydrocarbons are also present in both peaches and nectarines, surpassing organic acids in content (Lavilla et al., 2002; Ortiz et al., 2009; Seker et al., 2011)

Apricot (*Prunus armeniacaL.*): Apricot, shares a similar volatile organic compound (VOC) composition with other fruits in the family but possesses unique aroma compounds (Kafkas et al., 2005; Goliáš and Fruhwirt, 2008). Esters, although not the major aroma impact compounds, it contributes significantly to apricot's aroma profile (Solís-Solís et al., 2007; Goliáš et al., 2010). Moderate amounts of aldehydes and alcohols are also present, with their levels proportional to apricot maturity. Lactone compounds are minimal in apricot, with only a few identified. Terpenes and terpenoids, comprising about 10-12% of VOCs, show higher concentrations in extra-mature fruits, with linalool identified as a major contributor to apricot aroma (Defilippi et al., 2009).

Quince (*Cydonia oblonga Miller*): contains a high number of ester compounds, estimated at 77%, contributing extensively to its aroma (Schreyen et al., 1979; Umano et al., 1986; Tateo and Bononi, 2010). Aldehydes, although limited in studies, likely contribute to the green aroma in quince, with benzaldehyde being identified. Alcohol content in quince is relatively low. Terpenes play a significant role in quince flavors, with compounds like linalool and α-bergamotene being prominent contributors (Schreyen et al., 1979; Masyita et al., 2022). Ketones are not commonly reported in quince, but the fruit contains miscellaneous compounds such as acids and hydrocarbons. (Umano et al., 1986; Tateo and Bononi, 2010)

Loquat (*Eriobotrya japonica*): Loquat fruit contains a diverse array of volatile compounds, with esters constituting only 2.7% of the total volatile content (Pino et al., 2002; Hong et al., 2010; Chen et al., 2011). However, ethyl acetate and methyl cinnamate are notable esters contributing significantly to loquat's aroma. Aldehydes and ketones collectively contribute about 13.7% of the volatile compounds, with nonanal and benzaldehyde being prominent aldehydes. Alcohols, although relatively low in loquat fruit, play a role as precursors for ester synthesis. Ketones such as 3-hydroxy-2-butanone are more abundant, while β-ionone contributes to the character impact aroma (Chen et al., 2011; Besada et al., 2013). Terpenoids make up 5.2% of the volatile profile and contribute to fruity, spicy, and herbal aromas.

Plum (*Prunus domestica L.*): The aroma of plum is a conglomerate of different volatile compounds including esters, aldehydes, alcohols, ketones, terpenes, and lactones (Etievant et al., 1986; Gomez-Plaza and Ledbetter, 1994; Pino and Quijano, 2012). The major esters and their aroma notes are found in Table 2. Plum flavor contains high amounts of aldehydes (Etievant et al., 1986; Podestá et al., 2011). The Hexanal and (Z)-3-hexenal are the most important aldehydes contributing to plum flavor (Louw and Theron, 2012). Both plum fruit and brandies have high alcohol content which contributes to the aroma. Some alcohols identified in fruits and brandies are listed in table 1. The lactones in plums are few (Etievant et al., 1986; Gomez and Ledbetter, 1994). Lactones, together with hexanal (an aldehyde), and esters give plum a fruity flavor (Gomez and Ledbetter, 2010). Ketones are less abundant than other volatile compounds in plums (Etievant et al., 1986; Gomez and Ledbetter, 1994). The terpenes identified in plums are very few (Gomez and Ledbetter, 2010). Most common among them include *α*-bergamotene and *α*-caryophyllene. Plums also have moderate content of hydrocarbon and acid (Gomez and Ledbetter, 1994; Tešević et al., 2005; Gomez and Ledbetter, 2010).

Almond (*Prunus dulcis Mill. syn P amygdalus*): Almond, though not eaten raw unlike other *rosaceous* fruits, contains a volatile organic compound profile similar to others. Volatile organic compounds present in almonds are only available through the application of high temperatures. Unlike other *rosaceous* fruit volatile organic compound profiles, almond appears to contain no ester (Va'zquez-Arau´jo et al., 2009). However, it contains other volatiles including hydrocarbons such as pyrazines, pyrroles, and furan (Agila and Barringer, 2012). The content of aldehydes in almonds is about 28% and third most abundant compound after alcohols, also, alcohols account for over 30% and recorded as the second most abundant compounds in almonds (Agila and Barringer, 2012). Ketones and Lactones are very insignificant in almonds as it only accounts for less than 3% (Va'zquez-Arau´jo et al., 2009).

Factors that Influence the Composition and Concentration of VOCs in Rosaceae

The compositions and concentration of VOCs in *rosaceae* fruits and nuts are affected by so many factors such as genetic variances among the cultivars, fruits development and maturity, storage and processing, and environmental factors (Tressl et al., 1985; Matthais et al., 1992; Fellman et al., 2003). These of course may be the reason why some *rosaceae* families notably apple, strawberry, plum, quince, peaches, nectarines, etc., contain a very good number of volatile organic compounds with ester being the most abundant compounds, compared to cherry, raspberry, almond, with very few volatile organic compounds with very little or no ester compounds (Ménager et al., 2004; Pelayo-Zaldivar et al., 2005). Although *rosaceae* fruits and nut are in the same family, their genetic makeup is different hence the differences in the flavor and VOCs compositions. For instance, apple flavor is controlled by ester, cherry by aldehyde, raspberry by ketone, plum by lactones, etc. Their genetic background affects their flavors and VOCs compositions even within cultivars. For instance, high concentrations of hexyl acetate and butyl acetate have been reported in Cox's Orange Pippin,' 'Elstar', 'Golden Delicious', 'Jonagold' and 'Jublie Delbar' than in other cultivars (Fellamn et al., 2003; Matthais et al., 2005). 'Granny Smith' and 'Nico' contain high concentrations of ethyl butanoate in an apple. Apricot, orangé de Provence contained high levels of alcohols and acetates, 'Moniqui' contained higher γ-and ȡ-lactones, and 'Orangered' was high in terpenoids while 'Iranien' contained high levels of C_6-aldehydes such as hexanal and 2-hexanal (Matthais et al., 1992, 2005; Fellamn et al., 2003).

Fruit development and maturity were also implicated in the aroma and VOCs difference across the *rosaceae* family. The ethylene synthesis and a significant increase in CO_2 production during ripening play important roles in climacteric fruits unlike in non-climacteric fruit (cherry and strawberry) (Hakala et al., 2002). Generally, studies on the aroma profile of *Rosaceae* have reported an increase in volatile organic compounds as fruit ripening progresses (Tressl et al., 1985; Matthais et al., 1992; Fellamn et al., 2003). Fellman et al. (2003) reported that immature apple fruits produced low amounts of volatile compounds than mature fruit. Unequal distribution of volatile organic compounds in relation to immature and mature fruit in strawberrieshas been reported by several researchers (Ménager et al., 2004; Pelayo-Zaldivar et al., 2005). These studies showed that the ratios of methyl/ethyl esters were not dependent only on the cultivar, but also on the harvest date. The increase in VOCs as the fruit develops was also reported in other *rosaceae* including raspberry fruit, Forney (2001) reported that aroma volatiles increase during color formation and ripening.

Storage, environment, and processing such as cold, heat, irradiation, and chemical applications, all in one way or the other contribute to the variation in fruit flavor and VOCs compositions. Exposure of fresh products such as fruit and juice to O_2 over a long period can increase anaerobic respiration and lead to the development of off-flavors in some fruits. Mattheis et al. (2005) demonstrated that storage under controlled atmosphere (CA) conditions may reduce the possibility of ethylene production and subsequently alter the production of volatiles in apples. Chemical treatment such as calcium, widely used to prevent the development of bitter pit in some fruit has been reported to enhance the production of flavor compounds in a mature 'Golden Reinders' apple. A temporary inhibition or inactivation of enzymes responsible for volatile development in apples was observed at 46 °C. The study reported maximum ester production at 22 °C and a decline from 32° C – to 46°C (Guadagni et al., 1971). Further, the length or duration of storage also contributes to the total content and concentration of aroma compounds of fruits. Guadagni et al. (1971) reported that the highest volatile concentration in' Red Delicious' was recorded between 2-4 months and then declined following longer storage periods. In strawberries storage temperature and light affect their volatile content. Miszczak et al. (1995) reported a 7-fold increase in the volatiles content of strawberries following four days of storage. The effect of low O_2, CO_2 oxide, and storage temperature on the total volatile content of plum fruits has also been reported. Another study by Goliáš et al., (2010) reported that low oxygen atmospheres slowed down the production of esters and aldehydes without any effect on lactones and terpenes. In peach, there was a partial effect of storage on cultivars. For instance, the concentration of (Z)-3-hexen-1-ol was not influenced by cold storage in the cultivar Sweet Dreamcov, while the concentration of 1-hexanol increased in 'Sweet Dreamcov' and 'Elegant Lady' after 20 days of cold storage. The concentrations of ethanol, acetaldehyde, and ethyl acetate in the flesh of ripe sweet cherries were consistently enhanced by very low oxygen storage (Goliáš and Fruhwirt, 2008).

Recent Breeding strategies to Improve Flavor in Rosaceous Fruits

The long duration of breeding and lack of specificity in trait improvement; polyploidy nature, high heterozygosity, and clonal propagation associated with most *rosaceae* fruit species make them difficult to beenhanced throughconventional breeding methods (Barefoot, 2024). Hence, molecular breeding techniques have been tipped as most appropriate breeding procedure for improving flavors in *rosaceous* fruit just like in many other crop plants. Enhancing the flavor of fruits within the *rosaceae* family holds tremendous potential for bolstering consumer health by fostering increased fruit consumption (Farinati et al., 2017; Manzoor et al., 2023). However, achieving this goal is a multifaceted endeavor, influenced by genetic, environmental, and physiological factors. Historically, breeders have emphasized on traits such as size, color, and shelf life, often overlooking the major organoleptic property, flavor (Shulaev et al., 2008). Yet, there is a growing acknowledgment of the pivotal role flavor plays in fruit breeding. Flavor of fruits is also one of the cardinal desires of the fruits end user, both for fresh consumption and industrial processing purposes. Elevating flavor necessitates a profound understanding of the biochemical pathways and regulatory mechanisms at play (Sukumaran and Palayyan, 2022).

Marker-assisted breeding (MAB) and genomic selection are advanced molecular technique that leverage genetic information to select plants with desirable flavor traits efficiently (Klee, 2010). This method utilizes molecular markers linked to genes associated with flavor, allowing breeders to identify and select plants with superior flavor profiles without the need for extensive phenotypic evaluations. By analyzing the genetic makeup of various cultivars, breeders can pinpoint specific alleles that contribute to flavor compounds, including volatile aroma compounds. One of the main advantages of MAB is its ability to facilitate the introgression of beneficial flavor traits from wild relatives or other species into high-yielding commercial cultivars. This process helps to preserve important agronomic traits such as yield and disease resistance while enhancing the flavor quality of the fruit. MAB is particularly effective for complex traits like flavor, which are regulated by multiple genes and metabolic pathways. As genomic resources and databases continue to grow, the precision of MAB improves (Schauer et al., 2006; Tieman et al., 2006b; Zanor et al., 2009). Researchers can now more accurately correlate gene expression with the accumulation of flavor compounds, leading to more targeted and efficient breeding efforts. This enhanced precision allows breeders to develop fruit varieties with improved taste and nutritional profiles, addressing the complex nature of flavor traits and meeting consumer demands for high-quality produce (Schauer et al., 2006).

Transgenic modification method or the application of the principles of genetic engineering represents a cutting-edge technique for improving fruit flavor by making precise modifications to the genetic makeup of fruit crops (Tieman et al., 2006b; Zanor et al., 2009). This approach involves the introduction of specific genes that regulate flavor-related metabolic pathways. Through incorporating these genes, breeders can achieve targeted enhancements in flavor compounds, such as volatile aroma chemicals, which are crucial for developing more flavorful fruits. A significant advantage of transgenic approaches is their ability to introduce flavor-enhancing traits from wild relatives or other species that are difficult to crossbreed with commercial varieties (Zanor et al., 2009). For instance, genes (DNA fragments) responsible for producing specific flavor volatiles can be identified from a donor plant or any other organism; extracted and isolate the specific DNA fragment into a vector genome, cloned and the growing recombinant vector inserted into a recipient host plant, usually a high-yielding cultivars by a process called transformation. Then the transgene is crossed into an elite background. This results in fruits that are not only more flavorful but also maintain desirable agronomic traits like disease resistance, extended shelf life and yield increment (Tieman et al., 2006b; Zanor et al., 2009). Transgenic techniques also offer the capability to manipulate complex flavor profiles by stacking multiple genes that contribute to flavor quality. This method provides a comprehensive solution to the decline in flavor quality observed in many modern fruit varieties (Schauer et al., 2006; Tieman et al., 2006b; Zanor et al., 2009). By enhancing multiple aspects of flavor simultaneously, transgenic approaches address the broader issue of flavor degradation and ensure that fruits meet the high standards of taste expected by consumers.

Genome editing is the most recent molecular breeding approach and has been adopted in improving strawberry (Vondracek et al., 2024), apple (Malnoy et al., 2016; Osakabe et al., 2018; Pompili et al., 2020) for one trait or the other among the *rosaceae* fruit species. However, reports on many important breeding characteristics associated with fruit quality and production especially flavor are still lacking, indicating a need for streamlined genome editing approaches and tools in strawberry (Vondracek et al., 2024).

About three genome editing approaches have been reported which include: zinc-finger nucleases (ZFNs), transcription activator-like nucleases (TALENs), and CRISPR/Cas. Only CRISPR/Cas-mediated genome editing has been used, although it has not been widely implemented and optimized (Gu et al., 2021). According to Vondracek et al. (2024), the formers require substantial protein engineering while the later can be performed simply and easily through a change in the single guide RNA (sgRNA) sequence (Doudna and Charpentier, 2014). It is easier applied to diploid *rosaceae* than the octoploids (Martín-Pizarro et al., 2019). This is also due to simple nature of diploid genomes and complex nature of octoploids.

7.0 Challenges in Flavor Enhancement

Despite the potential of genetic engineering and MAB, there are challenges that breeders face in enhancing fruit flavor. These include issues related to affordability, consumer acceptance, and regulatory barriers associated with transgenic crops. Consumer acceptance of genetically modified organisms (GMOs) can be a significant hurdle, as public perception often influences market viability. Additionally, regulatory frameworks surrounding the approval and commercialization of transgenic crops can be complex and time-consuming. MAB, while a more viable alternative to transgenic approaches, is generally slower and may require more extensive research and development to achieve desired outcomes

Concerning gene editing approach, the high heterozygousity of octoploid *rosaceae* compared to the diploids make identification of target gene and design of efficient sgRNAs hard (Martín-Pizarro et al., 2019). Also, segregation of transgene-free edited plant genome can be impossible when the usually adopted asexual method for propagation of the *rosaceae* hybrids apply. However, conventionally, transgene-free genome edited plants are generated through sexual segregation, which is usually time consuming and labor-intensive (Gao, 2021).

Conclusions

Enhancing the flavor of fruits within the *rosaceae* family is a worthwhile endeavor with far-reaching benefits. By delving into the intricacies of flavor genetics and employing innovative breeding techniques, researchers and breeders can usher in a new era of more flavorful and nutritious fruits. This not only meets the demands of consumers but also strengthens the fruit industry as a whole. Flavor, often overshadowed by other traits, deserves its rightful place at the forefront of fruit breeding efforts. Through concerted focus and collaboration, we can unlock the full potential of flavor enhancement, enriching both our palates and our health.

Table 1: **Volatile Organic Compounds in Different Species of Rosaceae Fruits and Nuts**

s/n	**Apple**	**Ref**	**Strawberry**	**Ref**	**Cherry**	**Ref**	**Raspberry**	**Ref**
1	Ethyl-2-Methyl Butanoate Hexyl Acetate Hexyl Hexanoate Ethyl Butanoate Hexyl Butanoate (E)-2-Hexanal (E)-2-Hexenol β-Damascenone Propyl-2-Methyl Butanoate 4-Methylallylbenzene Butan-1-Ol Hexan-1-ol Hexyl Propanoate Butyl-2-Methyl Butanoate Hexyl-2-Methyl Butanoate Methyl-2-Methyl Butanoate Pentyl Acetate	Fellman et al., 2000; Honkanen and Hirvi, 1990; Mattheis et al., 1992; Young et al., 2004; Baldwin, 2002; Kitaura et al., (2004).	hexanal cis-3-hexanal trans-2-hexanal furaneol . mesifuran ethyl hexanoate ethyl butanoate methyl butanoate ethyl-2-methyl propanoate	Golaszewski et al., 1998; Honkanen and Hirvi, 1990; Manning, 1993; Perez et al.,1992; Roscher et al., 1997; Zabetakis and Holden, 1997; Baldwin, 2002. Kafkas and Payda, 2007; Larsen and Watkins, 1995.	Benzaldehyde Tolyl Aldehydes Phenylacetaldehyde Phenethyl Alcohol β-Damascenone . Linalool	Sun et al., 2010; Girard and Kopp, 1998; Mathias et al., 1992; Schmid and Grosch, 1986; Levaj et al., 2010; Mathias et al., 1991; Legua et al., 2017	H-(4-hydroxyphenyl-butan-2-one) (raspberry ketone) α-ionone β-ionone geraniol linalool benzyl alcohol ethyl hexanoate ethyl butanoate	Honkanen et al., 1980; Larsen and Poll, 1990; Larsen et al., 1992; Paterson et al., 2013; Robbins and Fellman, 1993; Baldwin, 200
2	**Apricot**	**Ref**	**Peaches/Nectarine**		**Plum**	**Ref**	**Quince**	**Ref**
	Beta-Ionone Linalool Gamma-Decalactone (E)-2-Hexenal Geraniol (E)-Beta-Damascenone Delta-Decalactone	Kafkas et al., 2012; Gokbulut and Karabulut, 2012; Greger and Schieberle, 2007; Greger and Schieberle,	benzaldehyde benzyl alcohol nonanol linalool ethyl hexanoate 3-methylbutanoate α-terpineol γ-hexalactone δ-decalactone . γ-undecalactone δ-undecalactone	Seker et al., 2011; Wang et al., 2009; Shiota et al., 1981; Baldwin, 2002; Cano-Salazar et al., 2012; Derail et al.,	Beta-Ionone Nonanal Hexyl acetate Ethyl Butanoate Linalool Hexanal (Z)-3-hexenal γ-octalactone, decalactone . γ-dodecalactone	Etievant et al., 1986; Gomez-Plaza and Ledbetter, 1994; Tešević et al., 2005; Pino and Quijano, 2012;	Ethyl 2-Methyl-2-Butenoate 2-Methyl-2-Butenal Benzaldehyde Hexanal β-Ionone α-Bergamotene	Umano et al., 1986; Erdoğan, et al., 2012; Mihara et al., 1987; Tateo and Bononi, 2010; Schreyen

		2007; Goliáš and Fruhwirt, 2012; Bureau et al., 2006.	γ-dodecalactone δ-dodecalactone α-pyrone pentyl-α-pyrone .	1999		Crowell and Guymon, 1973; Podestá et al., 2011.		et al., 1979.
3	**Loquat**	**Ref**	**Almond**	**Ref**	**Pear**	**Ref**		
	β-Ionone Phenylacetaldehyde (E)-2-Hexenal Ethyl acetate Methyl Cinnamate 2-Phenylethanol 3-Hydroxy-2-Butanone Hexanal 1-Hydroxycyclohexyl Phenyl Ketone 3,4,5-Trimethoxybenzoate Cis-Geranylacetone	Hong et al., 2010; Chen et al., 2011; Pino et al., 2002; Shaw and Wilson, 1982.	Benzaldehyde Heptanal (E)-2-Heptenal Benzyl alcohol 1,4-Butyrolactone .	Va’zquez-Arau´jo et al., 2009; Agila and Barringer, 2012	Ethyl 2-Methylbutanoate Ethyl (E,Z)-2,4-Decadienoate Ethyl butanoate Ethyl 2-Methylpropanoate Hexyl acetate Ethyl propanoate Ethyl hexanoate	Li et al. 2012; Takeoka et al., 1992; Suwanagul and Richardson, 1996; Versini et al., 1995; Rapparini et al., 2004; Shiota et al., 1981.		

Competing Interests

The authors declare that there are no conflicts of interest, financial or nonfinancial, directly or indirectly.

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